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LCA FOR AGRICULTURE

Regional carbon footprint analysis of dairy feeds for milk production in the USA

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Abstract
Purpose A greenhouse gas emissions analysis (carbon footprint) was conducted for cultivation, harvesting, and production of common dairy feeds used for the production of dairy milk in the USA. The goal was to determine the carbon footprint (grams CO_2 equivalents (gCO_2e)/kg of dry feed) in the USA on a regional basis, identify key inputs, and make recommendations for emissions reduction.
Methods Commonly used dairy feeds in the USA, such as soybeans, alfalfa, corn, and others, were identified based on a recent literature review and information from dairy farm surveys. The following input data for the cultivation and harvesting of dairy feeds were collected for five US regions: crop production data, energy input, soil amendments, and crop protection chemicals. Life cycle inventory input data were mainly collected from the US Department of Agriculture National Agricultural Statistical Service on a state-by-state basis as well as from state extension services forage crop budget estimates. In addition to consulting other life cycle assessment studies and published articles and reports, this cradle-to-farm gate carbon footprint analysis was conducted using the Ecoinvent™ unit processes in SimaPro version 7.1© (PRé Consultants 2009).
Results The final carbon footprint results (gCO_2e/kg of dry dairy feed) varied regionally depending on a number of factors such as lime and fertilizer application rates. The average national US carbon footprint results of the main feeds were: corn grain (390), corn silage (200), dried distillers grains with solubles (910 dry mill, 670 wet mill), oats (850), soybeans (390), soybean meal (410), winter wheat (430), alfalfa hay (170), and forage mix (160).
Conclusions and recommendations The southeast dairy region generally showed a relatively high level of carbon footprint for most feeds, and this is attributable to the higher application rates of both synthetic fertilizers and lime. The highest contributor to carbon footprint for most regions (apart from soybeans and soybean meal) was due to the application of inorganic nitrogen fertilizer. Efficient transfer of knowledge to farmers with regards to fertilizer best management practices such as precision application of farm nutrients may contribute significantly to reducing regional crop carbon footprints.

Keywords Carbon footprint · Dairy · Feeds · Milk production

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1 Introduction

The issue of environmental sustainability has become a prominent factor in decision-making for industries in

addressing environmental challenges, such as global climate change. The United States (US) dairy industry inaugurated a study to analyze greenhouse gas (GHG) emissions from milk production in the USA. The US dairy milk supply chain can be divided into the following major stages: (a) feed production, (b) milk production, (c) milk delivery to processor, (d) processing, (e) packaging, (f) distribution, (g) retail activities, (h) milk consumption, and (i) disposal. In a comprehensive report, within which this article is a part, each stage was analyzed independently and combined to provide the carbon footprint for the dairy supply chain (Thoma et al. 2012). This article here focuses on the production of dairy feed in the USA using sources of data at the level of individual states and then aggregates that information into five dairy regions.

While there have been a number of life cycle assessment (LCA) studies on crops in Europe, there have been relatively few in the USA. The Ecoinvent™ (PRé Consultants 2009) database contains many food and forage crop inventory profiles, but these are from European data sources. Hayashi et al. (2006) reviewed the progress of LCA studies in Europe for areas like renewable energy, animal production, and horticulture. In the USA, there were several LCA studies conducted on single crops such as switchgrass, soybeans, and corn associated with bioenergy product analyses, including studies by Kim et al. (2009 a, b), Spatari et al. (2005), Landis et al. (2007), Shapouri et al. (2002), Sheehan et al. (1998), Pradhan et al. (2009), and Rotz et al. (2010). A review of this literature indicated that no previous LCAs considered a large number of crops and dairy feeds, and therefore, our study fills an important gap in the USA with respect to updated analyses for agricultural crops and other dairy feeds.

2 Life cycle assessment methodology

2.1 Dairy feeds, goal, and scope

In this study, ISO protocols were followed and all GHG emissions were expressed as equivalent emissions of carbon dioxide (CO_2e.). Commonly used feeds for US dairy production were identified based on a recent literature source (Mowrey and Spain 1999) and information obtained from a nationwide dairy producer survey regarding the composition of dairy feeds (and other related topics) (Thoma et al. 2012—see Appendix A of Electronic Supplementary Material). Over 5,000 surveys were sent to dairy farmers through their Co-ops from January to May 2009 and a second mailing was conducted in June 2009. Of those surveyed, 531 responded. The main relevancy of this survey to this carbon footprint study was the identification of commonly used dairy feeds in the USA. Responses from the dairy farmer survey and the collection of other crop data were organized on the basis of five regions as shown in Fig. 1. The definition of dairy milk production regions was done through consultation with dairy experts (Thoma et al. 2012). The basis for selection of these regions was a combination of production practices and climatic conditions. There are over 130 distinct dairy feedstuffs included in the results of that survey.

Goal The main goal of this study was to determine the carbon footprint from the cultivation and harvesting of US dairy feeds on a basis of 1 kg of feed harvested or produced in units of grams CO_2 equivalents (gCO_2e)/kg of dry feed. An additional goal was to identify dairy feed inputs with the highest environmental impact to serve as a source of information for improvement in production and as a benchmark against which progress can be measured in the dairy industry.

Scope The scope was a cradle-to-farm gate analysis. In this article, we report on grain, forage crops, and other coproducts [e.g., dried distillers grains with soluble (DDGS) and soybean meal) for which inventory data were available from US government and university extension sources. In this study, we did not consider all of the 130 or so dairy feeds identified in the survey by Thoma et al. (2012). Table 1 shows the three major categories of dairy feeds considered in this study, including grain crops, forage crops, and coproducts. This study includes application of inorganic fertilizers, effects of crop residues, manure application, crop protection chemicals, and energy inputs required for cultivation and harvesting. According to a study by Landis et al. (2007), seed production comprised less than 1% of GHG emissions for corn and soybean. This result was generalized for all dairy feeds analyzed in this study by assuming all

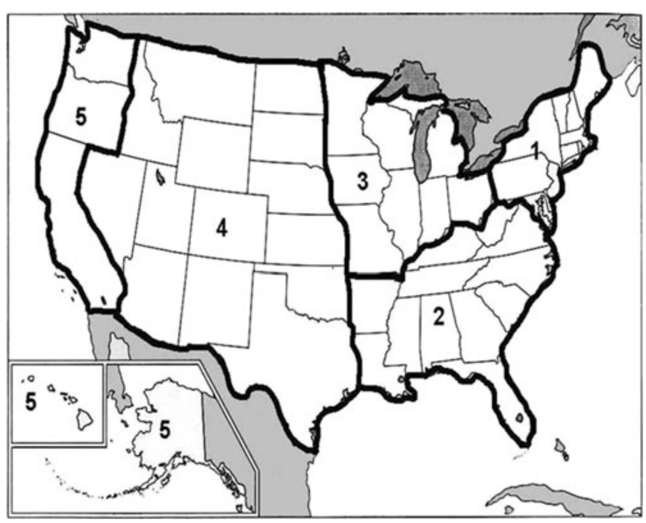

Fig. 1 Dairy production regions used for this study

Table 1 Dairy feeds analyzed in this study

Grain crops	Forage crops	Coproducts
	Alfalfa hay (16%)	
Oats (14%)	Alfalfa silage (16%)	
Soybean (13%)	Forage mix (16%)	DDGS, dry mill (10%)
Corn silage (65%)	Grain mix (15%)	DDGS, wet mill (60%)
Corn grain (15.5%)	Grass hay (16%)	Soybean meal (11%)
Winter wheat (13.5%)	Grass pasture (16%)	
	Grass silage (16%)	

Shown in parenthesis are the percentage moisture content for all feed analyzed in this study (NDSU 2011)

associated inputs for seed production were below cutoff criteria, and hence were excluded. Also, the scope of this carbon footprint analysis does not include incidental effects such as emissions from employee travel to or from the farm. Infrastructure elements, such as construction of buildings and farm equipment, were also excluded.

2.2 Functional unit

The functional unit for this carbon footprint study was 1 kg of dairy feed (grains, forage crops, and other coproducts) harvested or processed on dry matter basis.

2.3 Geographical boundaries

The geographical context of this carbon footprint study is the USA for dairy feeds grown and produced in the USA.

2.4 Allocation procedure

Most dairy feeds produced no coproducts, but for certain feeds, it was not possible to avoid allocation. For those feeds, allocations based on market value were used, as shown in Table 2. Section 3.1 explains the basis for allocation of nitrogen (N) inputs to corn and corn silage. Sections 3.1.1 and 3.1.2 explain in more detail the economic allocation to soybean oil and meal as well as wet and dried distillers grains with solubles. Five-year average commodity cost data from Illinois were used for economic allocation of soybean oil and meal, which was assumed to be representative of the national commodity market (USDA-IL 2010). Also, mass allocation based on a 5-year average yield provided by the National Oilseeds Processing Association was used for testing scenario cases, while economic allocation was adopted as the base case. Economic and mass allocation values for dried distillers grains with solubles from the thesis by Kodera (2007) were used in this study.

Table 2 Summary of allocation ratios and types used in this study

Coproduct	Economic allocation	Mass allocation
Soybean oil/meal/hulls	56.7:41.2:2.1	19.4:74:6.6[a]
DDGS dry/ethanol	30:70	52:48
DDGS wet/ethanol	24:76	51:49
Dairy feed/corn		Causal allocation
Corn/corn silage[b]		
Region 1		59:41
Region 2		91:9
Region 3		96:4
Region 4		95:5
Region 5		No data
		Causal relationship based on crop nitrogen requirements determined from reported yield

[a] CGB (2010)

[b] The large differences between regions are primarily determined by the relative production of each crop. More silage is grown in region 1 compared to corn grain than the other regions, and therefore, the allocation of shared inputs is not nearly equal

2.5 Inputs versus inventory data and possible limitations

Inputs such as fertilizer and fuel used for each crop production system were obtained from US government sources and the US literature. Inventory data underlying those inputs are largely from the Ecoinvent™ database (PRé Consultants 2009), which mostly represents European production. This presents a possible limitation to this study. However, European inventory data, while not geographically relevant, are technologically relevant for the inputs used in this US study because both US and European production uses modern technology. In addition, inventory data for many study inputs are simply not available yet based on US production.

3 Life cycle inventory analysis

A life cycle diagram describing the key inputs for each crop production system is shown in Fig. 2. The major inputs included: inorganic and organic fertilizer application on the farm, agrochemicals used to control pests, and farm energy use. Lime application on the farm was considered for some of the crops where data were available as well as effects of crop residues on direct and indirect nitrous oxide (N_2O) emissions. Energy use included gasoline, diesel, liquefied petroleum gas (LPG), natural gas, and electricity. GHG emissions for this analysis include: carbon dioxide (CO_2), methane (CH_4), N_2O, solvents, and refrigerants. Solvents and refrigerants were not directly included as

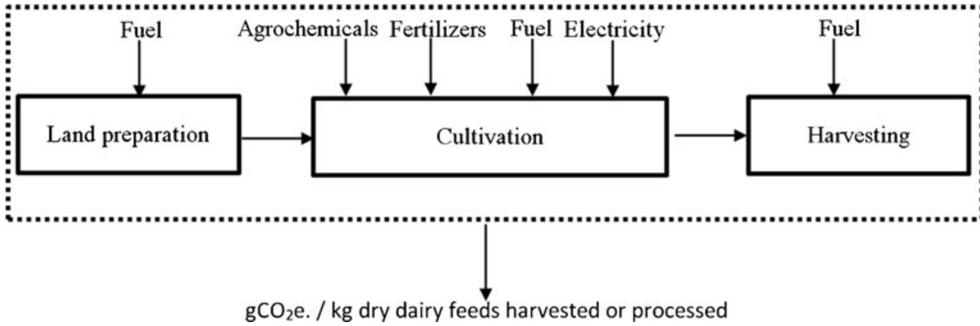

Fig. 2 Life cycle diagram for the cultivation and harvesting of dairy feed crops. *Dotted lines* represent the system boundary considered in this carbon footprint analysis

system inputs, rather these were incorporated by the use of Ecoinvent™ ecoprofiles (PRé Consultants 2009) for the various crop inputs. N_2O emissions from nitrogen fertilizer application for the degradation of crop residues and manure application were accounted for using IPCC (2006) guidelines for national GHG inventories (tier 1).

3.1 Production inputs and inventory for grains: corn, oats, soybeans, and winter wheat

Every year, the US Department of Agriculture (USDA) National Agricultural Statistical Service (NASS) conducts hundreds of farm surveys on cropping practice, chemical use, farm costs, and income. It is usually structured in a three-phase annual survey with specific goals. Phase I screens various farms for commodities and for potential inclusion in phases II and III, and this is done usually on a state-by-state basis. Phase II collects data on chemicals, fertilizer, and pesticides and has only one collection mode—personal interviews via-face-to-face contact. Phase III focuses on detailed economic information about the agricultural operation and the operator's household. Response rate from farmers has been highest for phase II with an average response rate of 80% from 2002 to 2006 and an average sample size of 5,465 according to the National Research Council (2008).

Table 3 summarizes the major crop databases and sources of the dairy grain crops. The USDA NASS databases were the primary source of crop production data for this study. Specific data obtained on a state-by-state basis included area harvested, yield, and total production. Average values for the harvested acres, yield, and production over the 5-year production period (2004–2008) were calculated and used. Annual crop production data for soybean, oats, wheat, corn grain, and silage for the 5-year period were obtained from the crop production summary reports from USDA NASS (2009a, 2007a). Appendix B of the Electronic Supplementary Material shows the computational spreadsheets of the major crops discussed here.

MacDonald et al. (2009) established that about 5% of US cropland receives animal manure, with corn land receiving over half of this applied manure. The percentage of planted acres receiving manure (manure share) was highest for corn and oats, being 11.6% and 9%, respectively. For all other grain crops, this area percentage for manure was approximately 1% or less. Therefore, we assume that only corn and oats receive manure as a fertilizer supplement. Dairy production regions needing supplementation with manure were identified by estimating the growth nitrogen requirements to meet crop production yields and comparing these with reported inorganic nitrogen inputs from the USDA NASS databases. The following sections explain in more details how the manure inputs were determined.

Corn Combined corn and silage input data for fertilizer and chemical application rates were obtained for states in regions 1, 2, 3, and 4, but no data were reported for region

Table 3 Crop databases and data sources for dairy grains

Summary of crop inventory and data source	
Soybean and soybean meal	Data sources
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA NASS (2007b)
Lime input	Pradhan et al. (2009)
Energy inputs	Sheehan et al. (1998)
Oats	
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA NASS (2006)
Lime input	Pradhan et al. (2009)
Energy inputs	Dartt and Schwab (2001)
Wheat	
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA (2007b)
Energy inputs	Piringer and Steinberg (2006)
Corn	
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA NASS (2006)
Energy inputs	Shapouri et al. (2002)
DDGS (dried distillers grains with solubles)	Hill et al. (2006)
	Wang (2001)
	Kodera (2007)
	Kim and Dale (2002)

5. USDA NASS database reported separate productivity data for corn grain and silage. Agrochemical chemical input data such as inorganic fertilizers and herbicides were reported for combined corn and silage land area. Productivity data indicated that region 5 contributed less than 1% toward the total corn production in the USA. MacDonald et al. (2009) in their report on manure usage for fertilizer estimated that 408 million kg of manure nitrogen was applied to corn grain and silage in the USA in 2007. The USDA NASS data for nitrogen application rates do not include manure contributions. In addition, the reported inorganic N application rates do not meet known crop requirements of approximately 0.54 kg N/bushel (bu) for corn grain and 5.19 kg N/mt for silage as defined by numerous crop production budgets (NDSU 1992). The amount of manure N required to reach the crop requirement was determined on a state-by-state basis using this equation: manure N = corn N growth requirement − synthetic N fertilizer application − residual N following rotation with soybeans. Using crop budgets for a corn–soybean rotation, it was estimated that approximately 23 kg N/ac was supplied in soybean residue (MSU 2010). The organic N from manure was applied in a manner to force the total N per crop to match the growth requirements mentioned above. Using a causal allocation based on the crop nitrogen requirements for both grain and silage, other crop inputs were allocated. Table 2 shows the allocation ratios used in this model for the various dairy production regions. Using this method, the total manure nitrogen applied to corn was approximately matched to the reported annual application rate of 408 million kg within a 4% margin. Specific inputs (e.g., lime) for the various crops are further explained in subsequent sections.

Soybeans In the case of soybeans, the USDA NASS (2009a, 2007a, b) had data such as quantity of inorganic fertilizer used, area harvested, crop productivity, chemical use, and other information for states in regions 2, 3, and 4. Soybean energy inputs and lime application rate data were obtained from Sheehan et al. (1998) and Pradhan et al. (2009), respectively. Inorganic nitrogen input data from USDA NASS (2007b) were included, while manure inputs were not because MacDonald et al. (2009) reported a manure share of approximately 1% of acres for soybean. Section 3.1.1 provides the sources of inventory data for the soybean meal–oil. The average of the carbon footprint in regions 2, 3, and 4 was used to represent regions 1 and 5 for which there were no data available.

Oats The primary source of data for fertilizer and chemical inputs for oats was from USDA NASS (2006). However, no input data (e.g., inorganic fertilizer and crop protection chemical) were reported for the states in region 2, and this is due to its relatively low oats productivity (5% of oats production). Due to the unavailability of input data for lime application for oat-producing states, the national average lime application rate for soybeans was assumed for the oats analysis (extension documents validated this estimate). Based on the N requirement recommendation of 0.5 kg N/bu and 40 kg N/ac (Beegle 1997), NASS reported inorganic N input data for dairy production regions 1 and 3 were low, requiring supplementation with manure. The reported inorganic N input data for regions 4 and 5 were sufficient to meet N requirement of oats. An estimated 20 kg N/ac of additional N from manure meets the reported yields, and this was applied to regions 1 and 3 on a state-by-state basis. This method does not take into account any nitrogen credit from prior rotation unlike in the case of manure GHG impact estimation for corn. Section 3.5 provides the details on energy inputs. Finally, due to lack of data for region 2, the inventory for this region was estimated by averaging regions 1, 3, 4, and 5.

Winter wheat This study focused on winter wheat because it accounts for 70% to 80% of the total wheat produced in the USA (USDA NASS 2009b) as compared to other types like durum and spring wheat. Productivity data were obtained from USDA NASS (2009a, 2007a); however, no data were available for the energy inputs on a state-to-state basis. Energy estimates for the production of wheat in the USA on a per hectare basis was obtained from Piringer and Steinberg (2006) for the wheat analysis. Manure impact was not considered for wheat primarily because it has less than 1% of acres applied with manure (MacDonald et al. 2009).

For all crops, input data for fuel and electricity consumption on the farm for crop production were obtained from the technical literature, state agricultural extension services, the US Department of Energy, the USDA, and other academic institutions (see Table 3). There are three regional interconnection grids in the USA, namely, Eastern Interconnection, Western Interconnection, and the Electric Reliability Council of Texas Interconnection. GHG emission factors (in gCO_2e/kWh) were constructed using Ecoinvent™ unit processes (PRé Consultants 2009) based on regional fuel mixes. Additionally, precombustion emissions and the transmission and distribution losses were included in the emission factor using regional interconnection grid data reported by Deru and Torcellini (2007). Section 3.5 of this article explains in more detail the assumptions and data sources for the specific crops for which energy input data were not available.

3.1.1 Soybean meal–oil–hull allocation

In the soybean meal analysis, additional processes were considered including transporting soybean to the crusher and crushing to recover oil and meal. The impact of

transporting soybean to the crusher was estimated as well as the impact of crushing with the use of data obtained from Sheehan et al. (1998), Pradhan et al. (2009), and Pollak (2010). The crushing and extraction energy required were updated based on a more recent study by Pradhan et al. (2009). Allocation to meal and oil were based on economic value of the coproducts from price data averaged over 2004–2008. The primary data source for prices was from Illinois, but is expected to be representative of the national commodity markets during the time period (USDA-IL 2010). Soybean meal allocation factors are shown in Table 2.

3.1.2 Dried distillers grains with solubles

Articles from the technical literature representing work done by LCA experts with corn ethanol and DDGS were used in this analysis. A thesis by Kodera (2007) performed a review of the effects of allocation method on LCA impacts of corn ethanol production by the dry milling process, for example, mass, energy, and value allocation as well as system expansion. Based on the allocation factor summary in this thesis and a study by Kim and Dale (2002), an allocation of the GHG burdens for corn ethanol production was made to DDGS in our model. As shown in Table 4, allocation factors varied widely and this resulted in some uncertainty for DDGS carbon footprint analysis. The DDGS GHG emissions values in this table were obtained using the allocation factors shown combined with GHG emissions for corn ethanol from three studies (Hill et al. 2006; Wang 2001; Shapouri et al. 2003) and DDGS production data from Hill et al. (2006). Detailed analysis of wet mill and dry mill DDGS can be found in Appendix B-6 of Electronic Supplementary Material.

3.2 Production inputs and inventory for forage crops: alfalfa, alfalfa silage, grass hay, grass pasture, and grass silage

To estimate the inventory for cattle forage production, crop production budgets produced by state agriculture extension specialists were collected and used as the primary source of input data. These budgets estimated the inputs needed to produce alfalfa, grass hay, silage, and pasture. These are not actual production records, but estimates prepared by agricultural extension agents with detailed knowledge of agronomic conditions in specific states. For this analysis, inventory data on fuel, electricity, fertilizers, soil amendments (N, P, K, sulfur, boron, and lime), and crop protection chemicals were used. When only purchase price for inputs was given, price was converted to quantity using information from budgets published on the same year that provided both price and quantity for the inputs in question. Pesticide application rates varied widely, depending on the type of pesticide. For budgets where only estimated pesticide purchase price was provided, available cost data were used to convert to quantities (Schnitkey 2004). MacDonald et al. (2009) reported that 6.9% (manure share) of hay and pasture land received manure as fertilizer. Because the budgets used to create the unit processes for these forage feeds report recommended total organic and inorganic nitrogen application rates together, it was assumed that 6.9% of the fertilizer applied was in the form of manure. In several cases, budgets provided total quantity of fertilizer, but did not specify the percentage breakdown for each. In this case, a ratio of 20:40:40 NPK for alfalfa was chosen, as it is a nitrogen fixer. For grass, we used 50:25:25.

Some budgets included custom costs for contracted services such as tilling, planting, or harvesting rather than providing explicit input estimates for each of these processes. Using figures from MSU Extension (MSU 2010) that showed custom costs per acre and fuel cost per acre for different practices, it was found that 16% of custom costs for tillage went to fuel, 12% to planting, 18% to fertilizers, and 18% of harvesting costs went to fuel. Over a 5-year period, a typical field is tilled and planted once, fertilized five times and harvested twice per year (10×); thus each practice was weighted by these estimated rates, giving tillage and planting a value of 1, fertilizing a value of 5, and harvesting a value of 10. As a result, a weighted average of 18% of custom costs was attributed to the consumption of diesel fuel.

There is a large difference in diesel use for hay, silage, and pasture. Most states provided budgets for hay, but fewer

Table 4 Allocation factors and GHG intensity of DDGS (see Appendix B-6)

	Energy	Mass	Economic	System expansion	References
Allocation factor to ethanol	0.57	0.48	0.70	0.80	Kim and Dale (2002); Kodera (2007)
Allocation factor to DDGS	0.43	0.52	0.30	0.20	
DDGS GHG emissions [kg CO_2e/kg DDGS (dry)]	1.60	2.30	0.91	0.53	
Corn ethanol (kg CO_2e/MJ ethanol)		0.0849			Hill et al. (2006)
		0.07			Wang (2001)
		0.062			Shapouri et al. (2003)

for pasture or silage. Using those few states that provided diesel use data for both (primarily regions 2 and 3), the average difference in diesel used to harvest hay or silage per short ton of crop was calculated. We assumed the dry matter yield was equivalent for pasture, hay, or silage. The only difference was harvesting and hauling. After finding the mean diesel use for hay for each region, we added ~1 gal per dry short ton of crop if harvested as silage and subtracted ~3 gal if kept as pasture.

3.3 Direct/indirect N_2O emissions

The IPCC (2006) tier 1 method was used to calculate direct and indirect N_2O emissions from managed soils for inputs such as synthetic and manure N fertilizer, N in crop residues (above and below ground residues) as well as CO_2 released by lime and urea-containing fertilizer. Direct N_2O release was estimated as 1% of N applied to soil released as N in N_2O. For indirect N_2O emissions, two major pathways were included. The first is the volatilization of N as NH_3 and oxides of N at a rate of 10% of applied N, and redeposition of these gases on water bodies where N_2O–N is emitted at a rate of 1% of the redeposited N. Leaching and runoff is the second pathway with a default leaching factor of 30% of applied N and an emission factor for N_2O–N of 0.75% of leached N. When urea ($CO(NH_2)_2$) is applied, it can be converted to ions like ammonium (NH_4^+) and bicarbonate (HCO_3^-) in the presence of urease enzymes and release CO_2. GHG emission from lime application is dealt with in Section 3.6. In this study, dinitrogen monoxide (N_2O) emissions for manure application is a combination of direct and indirect mechanisms as discussed above (see Appendix C of the Electronic Supplementary Material) including emissions from manure management systems (MMS).

The USDA NASS database does provide N fertilizer input data for crops (see Table 3); however, this database does not indicate the type of nitrogen fertilizer applied to crops. The production of different nitrogen fertilizers results in very different quantities of GHG emissions from their production. Therefore, an average US nitrogen fertilizer production profile was created for this study. Data on fertilizer consumption in the USA from the period of 2004–2007 was obtained and used to create the synthetic N ecoprofile for this analysis (Appendix D-1 and D-2 of Supplementary Documents). One of the N fertilizers, nitrogen solutions, was comprised of urea (35%), ammonium nitrate (40%), and water (25%) (Dyno Nobel Inc, MSDS 2010; Vitosh 1996).

For phosphorus fertilizer, a similar approach as for N fertilizer was taken by basing the mixture of phosphate fertilizers in proportion to their US production (USDA ERS 2009) as reported in Appendix D-3 of the Electronic Supplementary Material. Potassium and sulfur fertilizers as well as lime were treated similarly.

3.4 Crop protection chemicals

Insecticides, herbicides, and fungicides applied on the farm were considered in our analysis. In cases where the ecoprofile of a pesticide was not found in the Ecoinvent™ database in SimaPro 7.1© (PRé Consultants 2009), the chemical class was used. For instance, tebupirimphos which was not directly listed in the Ecoinvent™ database belongs to the organophosphorous class of compounds (PAN Pesticides Database 2009) and this was the ecoprofile used in our model. Rate of crop protection chemical application for soybean and winter wheat were all obtained from USDA NASS (2007b) while that of corn and oats were obtained from USDA NASS (2006). Forage crop protection data were obtained from state extension budgets as mentioned earlier.

3.5 On-farm energy

This analysis accounted for the following energy inputs on the farm: electricity, gasoline, diesel, LPG, and natural gas. Due to the lack of energy input information in the USDA NASS database, other sources were used to fill in the required data for the crop analysis. Energy input data for forage energy were from state extension documents as mentioned previously. Soybean energy input data were obtained from Sheehan et al. (1998) and represented 14 soybean-producing states, which together accounted for about 86% of the soybean produced in the USA. Additionally, energy input data for corn producing states were obtained from Shapouri et al. (2002) and represented about 80% of corn produced in the USA. In the case of oats, data for diesel use were obtained from Dartt and Schwab (2001). Due to lack of data on gasoline consumption for oats cultivation and harvesting, it was assumed that gasoline consumption was equal to one third of diesel consumption, based on diesel and gasoline inputs for other field crops, for example corn and soybeans. To fill data gaps, LPG and electricity inputs for corn and soybean were then averaged on a regional basis and used as an estimate for oats. Energy estimates for production of wheat in the USA on a per hectare basis was obtained from Piringer and Steinberg (2006).

3.6 Lime application

Lime application rates for soybean were obtained from Pradhan et al. (2009). In the case of oats, the national average of lime application rate for soybeans was assumed, which in our study (358 lb lime/acre) falls within the recommended range from two budgets that were obtained from

KSU (2003) and Crozier et al. (2004). Lime application data for corn grain and silage were estimated using a crop production budget (MSU 2010). While data on lime application rate were not available for wheat production, it appeared that lime was seldom used. For example, only 9% of wheat land area has ever been treated with lime based on a 1997 survey by USDA (Heimlich 2003). According to a US Geological Survey (USGS 2007) approximately 10.8 billion and 32 million kg of limestone and quicklime were applied in the US agricultural sector, respectively. As a result, every kilogram of an average US lime comprises 0.997 kg $CaCO_3$ and 0.003 kg of CaO. Final GHG intensity of lime accounts for both the production and its application on the field. Due to the on-farm application of calcium carbonate to acidic soils, CO_2 is released, which was accounted for in this study using the emission factor from the IPCC (2006) (see Section 3.8 for emission factor).

3.7 Crop residue effects on direct/indirect N_2O emissions

In this study, the 2006 IPCC guidelines for national GHG inventories (tier 1) was used to account for the N_2O emissions from the degradation of crop residues above and below ground. The average regional yields for various dairy feeds were converted on a dry weight basis to obtain a kilogram dry crop per harvested area. In addition, other parameters like the N content and weight of dry matter residue above and below ground allowed for the final estimation of kilogram N above and below ground of crop residue per kilogram of crop harvested. Appendix E of the Electronic Supplementary Material shows the detailed analysis of N_2O emissions of crop residues.

3.8 Emission factors for fertilizer, crop protection chemicals, and energy input

The emission factors are shown in Table 5 for the production and use of various fertilizers, lime, and energy inputs. Emission factors for pesticides are listed in the Electronic Supplementary Material (see Appendix F).

3.9 Data quality

The pedigree matrix derived from Frischknecht et al. (2007) was used to assess the quality of data, primarily fertilizer and other N_2O emissions, crop protection chemicals, and

Table 5 Emission factors for farm input: fertilizer, agrochemical, and energy

Farm inputs		Emission factors	Sources
Fertilizer	N	3.871 kg CO_2e/kg N in US mix N fertilizer due to manufacturing of N fertilizer	USDA ERS (2009)[a]
		0.633 kg CO_2e/kg N in US urea in US mix of N fertilizer due to field emissions CO_2	IPCC (2006)
		6.205 kg CO_2e/kg N in US mix of N fertilizer due to direct and indirect N_2O field emissions	Ecoinvent Database (PRé Consultants 2009)
	P	3.028 kg CO_2e/kg P in US mix P fertilizer due to manufacturing of P fertilizer (applied as P)	USDA ERS (2009) Ecoinvent Database (PRé Consultants 2009)
	K	0.573 kg CO_2e/kg K in US mix K fertilizer due to manufacturing of K fertilizer	USDA ERS (2009) Ecoinvent Database (PRé Consultants 2009)
	S	3.855 kg CO_2e/kg S in fertilizer	Ecoinvent Database (PRé Consultants 2009)
Agrochemicals	Lime	0.0158 kg CO_2e/kg lime due to manufacturing	USGS (2007)[b]
		0.4400 kg CO_2/kg $CaCO_3$ due to application on farm	
Fuel	Gasoline	10.96 kg CO_2e/gal	Deru and Torcellini (2007)
	Diesel	11.89 kg CO_2e/gal	
	LPG	7.66 kg CO_2e/gal	SEIT (2006)
	NG	7.72 kg CO_2e/CCF	
Electricity	US region	kg CO_2e/kWh	
	US Avg	0.823	Deru and Torcellini (2007)
	Eastern	0.867	
	Western	0.653	
	ERCOT	0.928	

LPG liquefied petroleum gas, *ERCOT* Electric Reliability Council of Texas, *NG* natural gas, *Avg* average

[a] Source: http://www.ers.usda.gov/Data/fertilizeruse/

[b] http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/myb1-2007-stonc.xls and http://minerals.usgs.gov/minerals/pubs/commodity/lime/myb1-2007-lime.xls

energy inputs. Six characteristics of data quality were included: *reliability*, *completeness*, *temporal correlation*, *geographic correlation*, *further technological correlation*, and *sample size*. This was done by assigning a set of scores from 1 to 5 after a careful analysis of each data source (see Appendix G of Electronic Supplementary Material). Using some basic uncertainty (U_7) factors provided in Table 7.2 of Frischknecht et al. (2007) and assessing the data sources according to the six characteristics mentioned above, the square of geometric standard deviation (SD_{g95}) was calculated using Eq. 1:

Equation 1 For calculating SD_{g95}

$$SD_{g95} = \sigma_g^2 = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_7)]^2}} \quad (1)$$

where U_1 = uncertainty factor of reliability, U_2 = uncertainty factor of completeness, U_3 = uncertainty factor of temporal correlation, U_4 = uncertainty factor of geographic correlation, U_5 = uncertainty factor of other technological correlation, U_6 = uncertainty factor of sample size, and U_7 = basic uncertainty factor.

By assuming a log-normal distribution of uncertainty, the estimated SD_{g95} was used to calculate an upper and a lower bound of the 95th percentile confidence interval for the various dairy feeds on a national basis (Table 6). The geometric mean (in micrograms) was used to estimate the lower and upper bound (gCO2e/kg feed) using Eqs. 2 and 3 (Frischknecht et al. 2007).

Equations 2 and 3 For calculating the lower and upper bound values of carbon footprint

$$\text{Lowerbound} = \frac{\mu_g}{\sigma^2{}_g} \quad (2)$$

$$\text{Upperbound} = \mu_g \times \sigma^2 g \quad (3)$$

4 Life cycle greenhouse gas impact assessment and interpretation of results

4.1 General assumptions for life cycle impact analysis

In estimating the carbon footprint, the GHG emissions were converted to CO_2 equivalents using global warming potentials (GWP) in the "IPCC 2006 100a" method in SimaPro 7.1© (PRé Consultants 2009); GWP is 1 for CO_2, 298 for N_2O, and 25 for CH_4 (Forster et al. 2007). The effects of other greenhouse gases emitted in minor amounts such as refrigerants, halons, and certain chlorinated solvents were also accounted for.

Table 6 Cradle-to-farm gate carbon footprint results of commonly used feeds by region and on national basis (gCO_2e/kg dry feed)

	Production region							
	1	2	3	4	5	Lower bound	Central bound (geometric mean)[a]	Higher bound
Alfalfa hay	190	270	140	140	150	140	170	210
Alfalfa silage	200	280	150	150	160	150	180	220
Corn grain	360	440	370	440	**400**	270	390	560
Corn silage	160	260	190	220	**210**	140	200	290
DDGS, dry mill	910	910	910	910	910	590	910	1,400
DDGS, wet mill	670	670	670	670	670	430	670	1,400
Forage mix	160	260	140	140	150	130	160	200
Grain mix	530	590	520	570	550	450	550	670
Grass hay	300	470	280	270	330	260	320	390
Grass pasture	240	410	250	220	280	130	270	560
Grass silage	310	480	290	280	340	270	330	410
Oats	800	**800**	580	1,000	1,140	580	850	1,240
Soybean	**410**	520	330	390	**410**	270	390	580
Soybean meal	460	540	400	430	450	420	460	490
Winter wheat	380	400	510	500	390	300	430	600

For crops with data presented in bold, no data for production was available; the average of results from other regions was adopted

[a] The geometric mean represents the US national greenhouse gas profiles for the various dairy feed with their respective ranges (lower/upper bound) estimated using the square of geometric standard deviation as shown in Eq. 2

4.2 Regional greenhouse gas emissions of dairy feeds

Table 6 summarizes the regional GHG emissions of dairy feeds on a per dry kilogram basis. Careful examination of the table reveals that there is significant variability among the regions for several feeds. Nearly all of the highest values are associated with region 2, and this appears to be driven primarily by greater nitrogen and lime inputs. The exception is the production of oats in region 5, which is nearly double the lowest value. This is as a result of much higher application rates for N reported in California; approximately three times the rates applied in other areas. This is partially offset by larger yields; however, the yield is only 1.5 to 1.7 times that of other regions. Grass has a higher carbon footprint than other forage crops and nearly as high as corn grain. Regional results for each feed analyzed were combined to estimate the national carbon footprint (see Table 6). Overall, processed coproducts like wet mill and dry mill DDGS and soybean meal show higher GHG emissions.

Results in Table 6 can be compared to recent literature values, though some of these studies occurred in different geographic contexts. Landis et al. (2007) modeled the agrosystem material flows for US corn and soybean by employing the greenhouse gases, regulated emissions, and energy use in transportation (GREET) model. The following results were obtained by Landis et al. (2007): 310–680 gCO_2e/kg of dry corn and 120–290 gCO_2e/kg of dry soybean. The carbon footprint results for corn and soybean at the farm stage from GREET (2010) were 290 and 200 gCO_2e/kg of dry crop, respectively. Two separate studies by Kim and Dale (2009a—40 counties in the USA) and Kim et al. (2009b—eight counties in the USA) estimated 360±100 and 540±290 gCO_2e/kg of dry corn grain, respectively, for US corn-producing counties. In our study, the national carbon footprint of corn grain was estimated to be 390 gCO_2e/kg of dry corn grain, with upper and lower bounds of 270 and 560 gCO_2e/kg of dry corn grain. Additionally, a value of 300 gCO_2e was estimated for 1 kg dry corn at field using the United States Life Cycle Inventory database in SimaPro (PRé Consultants 2009). The GHG emissions of 1 kg corn silage at the farm gate for the Swiss production processes using Ecoinvent Database was 190 gCO_2e/kg of dry corn silage, a value close to corn silage for our study in Table 6. A value of 620 gCO_2e/kg dry soybean was obtained from the Denmark LCA food database in SimaPro (Denmark LCA Food 2011 and PRé Consultants 2009). Dalgaard et al. (2008), using the EDIP 97 database (a Danish LCA methodology) in SimaPro (PRé Consultants 2009), analyzed the GWP of 1 kg (dry) of soybean meal to be 721 gCO_2e while Pelletier (2008) in the study of the environmental performance in the US broiler poultry sector estimated 297 gCO_2e. Finally, another European study by Van der Werf et al. (2005) estimated the GHG emissions for the production of 1 kg of wheat and barley to be 375 and 400 gCO_2e/kg of dry crop, respectively, while the Denmark LCA food database (PRé Consultants 2009) estimates 710 and 570 gCO_2e for 1 kg of dry wheat and oats, respectively. Taking into account the differences in modeling tools, study scope, and geographical context for the different studies, results from the literature are generally comparable to those obtained in this study. The following sections will display the results in more detail with regard to the relative importance of specific crop life cycle stages and inputs.

4.2.1 Soybean

Soybean showed a lower carbon footprint than some crops due to lower inorganic nitrogen fertilizer application, and this was largely due to the fact that it is a nitrogen-fixing crop. However, significant contributors to the various regional results are: lime application, gasoline, diesel, and N_2O emissions from soybean residues, as shown in Fig. 3. Together, they contributed about 70–86% of the overall GHG emissions in each productive dairy region. Interesting was the relative impact of lime input on the overall regional footprints. Lime input data for regions 2 and 3 for the soybean-producing states were relatively comprehensive (60% and 100% of states reporting, respectively). For region 4, data for lime application were available for just two states out of the six soybean-producing states. Another probable reason could have been the acidic nature of soils in regions 2 and 3 requiring more lime to increase soil pH for plant growth. Emissions of N_2O from crop residues were large compared to N_2O released from the application of N fertilizers for soybeans, a distinctly different feature compared to other crops. Approximately 65% of GHG emissions from N fertilizers were due to field application, with about 35% from manufacture, as also seen from the data in Table 5. Although it was not exactly clear why the states in the midwest (region 3) used relatively lower amounts of diesel, one possible reason was the effect of the Midwest Clean Initiative Diesel (EPA 2011) which encourages operational changes, technological improvements, and use of cleaner fuels for powering equipment. Finally, using the pedigree matrix, the standard deviation with 95% confidence interval for inorganic fertilizer, crop protection chemicals, and energy inputs was estimated to be 1.51, 1.21, and 1.57, respectively (see Appendix G-11 of the Electronic Supplementary Material).

4.2.2 Oats

The major contributors to the oats carbon footprint in the USA (Fig. 4) were identified to be inorganic nitrogen and phosphate fertilizers, manure, lime application, diesel, and the impact of N_2O emissions from oat residues, which together makes up approximately 72–92% of the overall

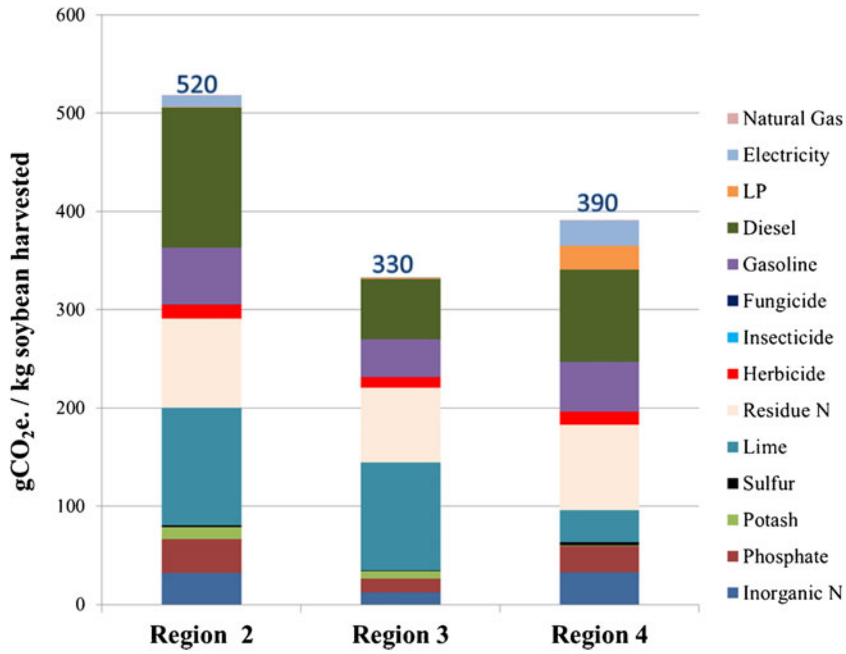

Fig. 3 Carbon footprint profile of soybeans harvested in the USA

footprint in each region. The regional variation in carbon footprint was due to the impact of fertilizer application rate. For example, dairy region 5 shows an unusually high carbon footprint of 1,100 gCO_2e/kg of oats harvested, due to high fertilizer N application. Furthermore, results from California in region 5 may not be representative of the other states in this region. About 65% of inorganic N fertilizer GHG emissions was from field application and 35% was due to manufacture.

The impact of crop residues remains fairly constant across the various regions for oats, contributing about 9% on national average towards the carbon footprints reported. However, the use of manure to supplement inorganic fertilizers in regions 1 and 3 contributed 21% and 26%, respectively, towards the regional footprints. Finally, in the case of oats, the standard deviation with 95% confidence for inorganic fertilizer, chemical protection, and energy inputs was estimated to be 1.51, 1.24, and 1.36, respectively (see Appendix G-11 of the Electronic Supplementary Material).

4.2.3 Corn grain and silage

Inorganic fertilizers, manure, phosphates, lime, diesel as well as the impacts of grain drying and N_2O emissions due to residues contributed approximately 80–90% towards the regional C footprint of corn grain (Fig. 5). In the corn silage analysis in Fig. 6, inorganic fertilizers, manure, phosphates, lime, diesel as well as the impacts of drying and N_2O emissions due to residues contributed about 73–90% towards the corn silage footprint for each dairy region. The

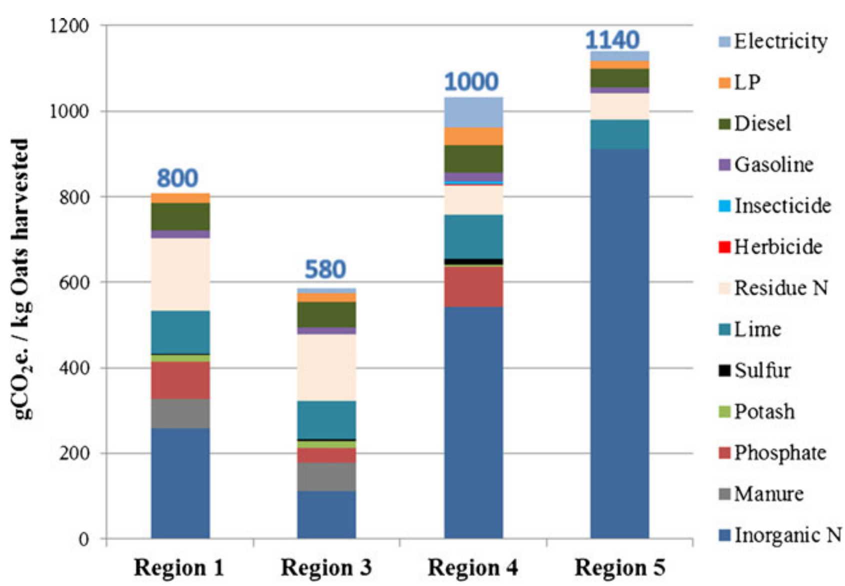

Fig. 4 Carbon footprint profile of oats harvested in the USA

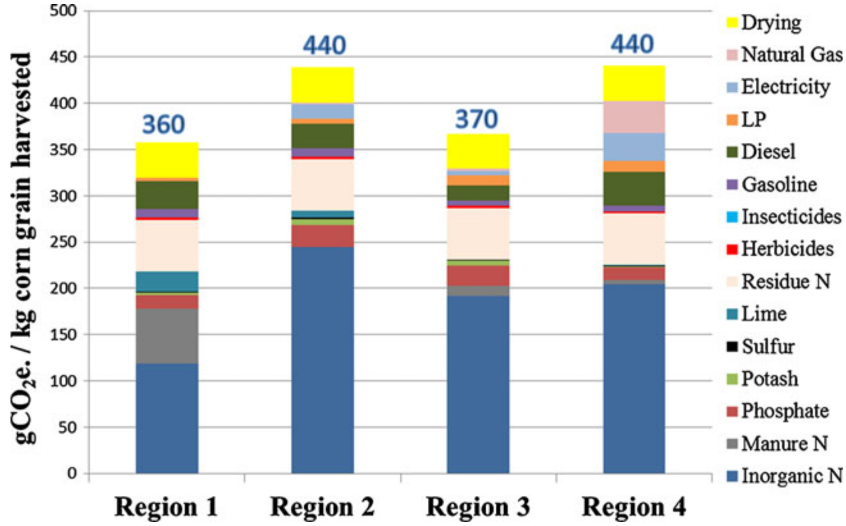

Fig. 5 Carbon footprint profile of corn grain harvested in the USA

contribution of the MMS to the GHG emissions for both crops was small (always <2%). Generally, the GHG emissions for corn grain with respect to the various dairy regions were about two times greater than for the corn silage. The comparatively larger emissions for corn grain compared to silage were mainly due to the allocation method applied from Section 3.1, under "Corn". Figure 5 shows high contributions of inorganic fertilizer from region 2, as this is the reason why additional manure was not added to supplement plant growth in this region. Interestingly, Fig. 6 shows a relatively high contribution for the use of natural gas for region 4 and this was primarily due to extremely high level of energy requirements from corn farms in Texas. In the final analysis, the standard deviation with 95% confidence for fertilizer, chemical protection, and energy inputs was estimated to be 1.51, 1.21, and 1.26, respectively, (see Appendix G-11 of the Electronic Supplementary Material) using the pedigree matrix.

4.2.4 Winter wheat

Regions 3 and 4 showed the highest carbon footprint (Fig. 7), largely due to the high rate of application of inorganic nitrogen fertilizers by farmers. Inorganic nitrogen and phosphate fertilizers, diesel, and the impact of N_2O releases contributed 93–95% of the overall GHG emissions in each dairy region. As in other crops, about 65% of inorganic N fertilizer GHG emissions was from field application and 35% was due to fertilizer manufacture.

On the whole, the carbon footprints for all dairy feed crops analyzed in this study were within the range 160–1140 gCO_2e/kg of dry feed. Various contributions of different farm inputs varied on a regional basis and this was mainly due to the different fertilizer, liming, and energy requirements depending on location, soil properties, and climate.

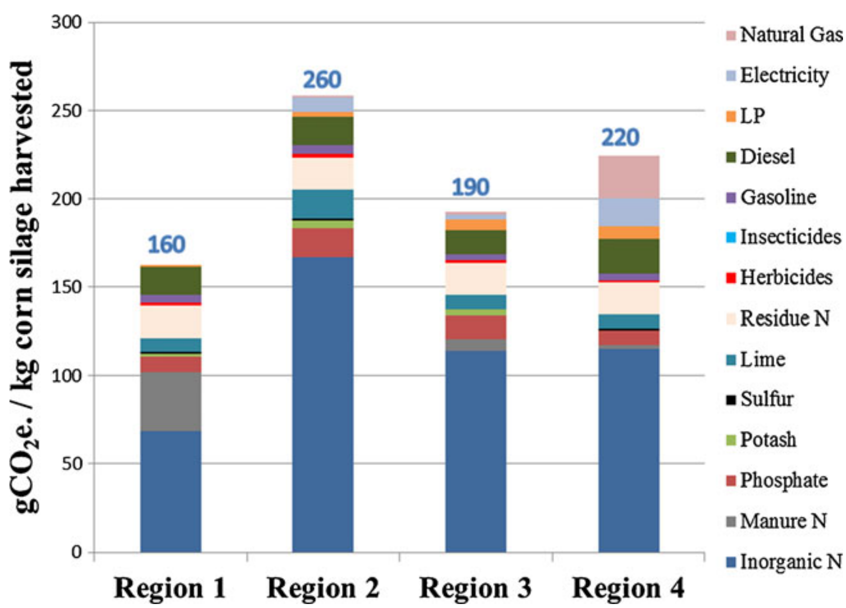

Fig. 6 Carbon footprint profile of corn silage harvested in the USA

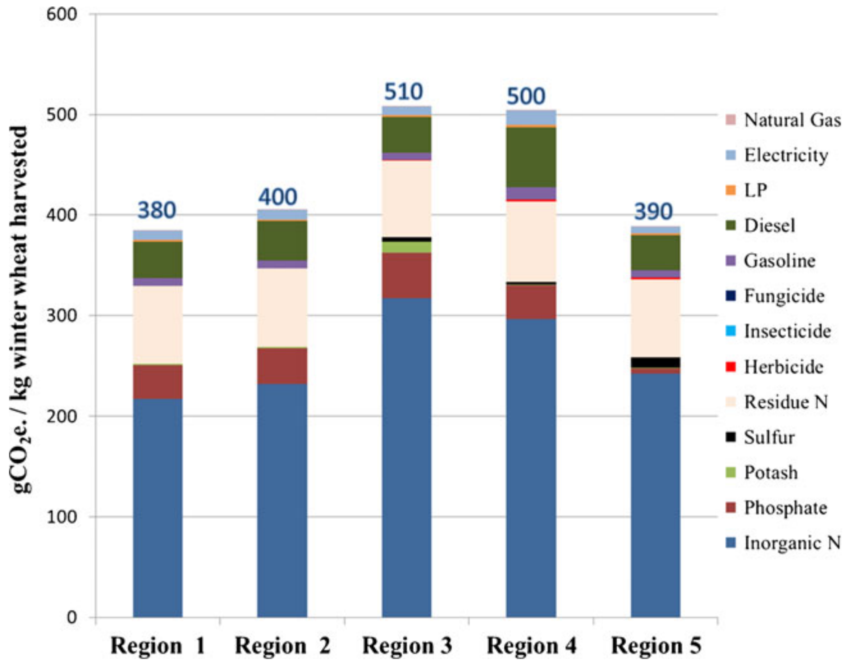

Fig. 7 Carbon footprint profile of winter wheat harvested in the USA

4.2.5 Forage crops: alfalfa hay, alfalfa silage, grass hay, grass pasture, and grass silage

The major contributors towards the regional footprints for both alfalfa hay and silage were identified to be due to crop residue, phosphate, lime, diesel, and electricity. In all regions, these factors contributed between 80% and 90% toward the overall regional footprint. However, impacts due to the application of potash, boron, crop protection chemicals, and use of gasoline were minimal ranging between 4% and 14% toward the carbon footprint for both alfalfa hay and silage. Contributions to carbon (GHG) footprint due to the application of inorganic fertilizer for both alfalfa hay and silage was less than 10% in all dairy production regions for which input data were available, and this low result was not surprising given that alfalfa is a nitrogen-fixing crop.

Grass showed a higher carbon footprint than other forage crops and nearly as high as the corn grain. Grass typically requires less maintenance and inputs, but produces lower yields than many other crops. In addition, there is much higher variability and uncertainty in actual yield than for other commodity crops. Region 2, which has the highest carbon footprint for grass and hay production, also had higher fuel, lime, and nitrogen use based on the available budget information. In all the different types of grass analyzed, inorganic fertilizers were the major contributors ranging from 34% to as high as 90% toward the footprint in the case of grass pasture. Lime contributions were significant for regions 1, 2, and 3, ranging between 13% and 19% for all grasses analyzed, but under 10% for regions 4 and 5. This reflects the acidic nature of soil in regions 1 to 3.

Finally, the standard deviation with 95% confidence for all inputs of alfalfa and grass were both estimated to be 1.22. Emission ranges varied significantly on a regional basis. The ranges reported in gCO_2e/kg dry forage feed were as follows: 140–270 (alfalfa hay), 150–280 (alfalfa silage), 270–470 (grass hay), 220–410 (grass pasture) and 280–410 (grass silage). The GHG emissions of 1 kg grass hay and silage at the farm gate for the Swiss production processes using Ecoinvent™ database (PRé Consultants 2009) were analyzed to be 180 and 220 gCO_2e/kg of dry feed, respectively, and somewhat lower than our results.

5 Conclusions and recommendations

In this carbon footprint study, the main goal was to estimate the GHG emissions from the cultivation and harvesting of dairy feeds on a basis of one dry kilogram of dairy feed harvested or produced (gCO_2e/kg of dry dairy feed). Table 6 shows the cradle-to-farm gate carbon footprint results obtained for all dairy feeds analyzed in this study. There were large differences in GHG emissions among the different dairy crops, with corn silage showing the lowest, while oats and DDGS displayed the highest. This variability was largely driven by fertilizer and energy utilization intensity as shown in Figs. 3, 4, 5, 6, and 7. There was some variability in carbon footprint for any crop from region to region, driven by regional differences in energy and lime use, but this variability was smaller than inter-crop variability.

The highest contributor to carbon footprint was the on-farm application of inorganic N fertilizer except for the leguminous feeds, whereas the fertilizer input categories P,

K, and S accounted for relatively small impacts for all crops. About 65% of inorganic N fertilizer GHG emissions was due to N_2O release upon application, whereas 35% was from fertilizer manufacture. N_2O emission contribution from crop residues was also significant for most crops. With N fertilizer input being the largest contributor to GHG emissions, much effort should be targeted toward lowering emissions associated with their production and use on the farm. Additionally, the efficient transfer of knowledge to farmers with regards to fertilizer best management practices might help reduce emissions on the farm. The use of crop protection chemicals was not so significant however, and energy use impacts varied widely from region to region, likely due to differences in climate, energy conservation programs, and need for crop drying. Finally, on the energy front, there is the need to promote the use of safe and cleaner forms of energy to help reduce climate active GHG emissions associated with the energy input needed by farmers.

This study highlights key crop inputs that are the drivers for emissions of greenhouse gases from the cradle-to-gate cultivation and harvesting for US dairy grain and forage crops. These crop results are equally applicable for uses other than dairy products; for example food production in general and bioenergy. Hopefully, these results will be useful for reducing GHG emissions by guiding efforts to modifying agricultural practices with respect to fertilizer application, use of manure, and energy consumption.

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References

Beegle D (1997) Estimating manure application rates. Agronomy fact sheet 55. Available at: http://juniataccd.org/programs/NMP/agronomy55.pdf

CGB (2010) CGG Enterprise Inc. http://www.cgb.com/browse.asp?page=339. Accessed 23 Jan 2010

Crozier CR, Osmond DS, Dunphy EJ, Fisher L, Heiniger RW, Johnson SE, Jordan DL, Weisz R, Hardy DH (2004) Lime and fertilizer suggestions—field, pasture, and hay crops. In 2012 North Carolina agricultural chemicals manual. The College of Agric. and Life Sci, North Carolina State Univ, Raleigh, p 40 Available: http://ipm.ncsu.edu/agchem/4-toc.pdf. Accessed 1 Dec 2010

Dalgaard R, Schmidt J, Halberg N, Christensen P, Thrane M, Pengue W (2008) LCA of soybean meal. Int J Life Cycle Assess 13:240–254

Dartt A, Schwab G (2001) Crops and livestock budgets estimates for Michigan. Agricultural economics report 609. Available at: http://www.aec.msu.edu/aecreports/budgets01.htm

Denmark LCA Food Database (2011). Available at http://www.lcafood.dk/products/crops/cashcrops.htm. Accessed 16 Jan 2011

Deru M, Torcellini P (2007) Source energy and emission factors for energy use in building, technical report NREL/TP-550-38617. Available at: http://www.nrel.gov/docs/fy07osti/38617.pdf

Dyno Nobel Inc, MSDS (2010) Material safety data sheet, Dyno Nobel Inc. MSDS # 1138. Available at: http://www.irmteam.com/Product_Sheets/MSDS-dynonobel-UAN32.pdf

EPA (2011) Environmental Protect Agency. USA http://www.epa.gov/midwestcleandiesel/. Accessed 23 Feb 2011

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Prinn G, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin Min D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M, Wernet G (2007) Overview and methodology. Ecoinvent report no 1. Swiss Centre for Life Cycle Inventories, Dübendorf

GREET (2010) The greenhouse gases, regulated emissions, and energy use in transportation model. Argonne National Laboratory, U.S. Department of Energy. Available at: http://greet.es.anl.gov/main. Version 1.8d. Accessed 10 Jan 2011

Hayashi K, Gaillard G, Nemecek T (2006) Life cycle assessment of agricultural production systems: current issues and future perspectives. In: Hu SH, Bejosano-Gloria C (eds) Good agricultural practice (GAP) in Asia and Oceania. Food and Fertilizer Technology Center, Taipei, pp 98–110

Heimlich R (2003) Agricultural resources and environmental indicators. Agriculture handbook no. AH722. Washington, DC: USDA Economic Research Service. Available at: http://www.ers.usda.gov/publications/arei/ah722/arei4_4/AREI4_4nutrientmgt.pdf

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci 103:1206–11210

IPCC (2006) Guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston H, Buendia L, Miwa K, Ngara Tand Tanabe K (eds). Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm

Kim S, Dale B (2002) Allocation procedure in ethanol production system from corn grain: I. System expansion. Int J Life Cycle Assess 7:237–243

Kim S, Dale B (2009) Regional variations in greenhouse gas emissions of biobased products in the United States—corn-based ethanol and soybean oil. Int J Life Cycle Assess 14:540–546

Kim S, Dale B, Jenkins R (2009) Life cycle assessment of corn grain and corn stover in the United States. Int J Life Cycle Assess 14:160–174

Kodera K (2007) Analysis of allocation methods of bioethanol LCA, M.Sc. Thesis, CML, Leiden University, Netherlands, pp 23

KSU (2003) http://www.ksre.ksu.edu/library/crpsl2/mf2586.pdf. Accessed 1 Jan 2010

Landis E, Miller A, Theis L (2007) Life cycle of the corn−soybean agroecosystem for biobased production. Environ Sci Technol 41:1457–1464

MacDonald J, Ribaudo M, Livingston M, Beckman J, Huang W (2009) Manure use for fertilizer and for energy: report to congress. Administrative publication number: 037. Available at: http://www.ers.usda.gov/publications/ap/ap037/

Mowrey A, Spain N (1999) Results of a nationwide survey to determine feedstuffs fed to lactating dairy cows. J Dairy Sci 82:445–451

MSU (2010) Michigan State University Extension. https://www.msu.edu/user/steind/. Accessed 1 Jan 2010

National Research Council (2008) Understanding American agriculture: challenges for the agricultural resource management survey. Panel to review USDAs agricultural resource management survey. Committee on national statistics, division of behavioral and social sciences and education. The National Academies Press, Washington, DC

NDSU (North Dakota State University, USA) (1992) Fertilizing corn grain, popcorn, silage corn, and sweet corn. Available at: http://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf722w.htm. Accessed 23 Feb 2011

NDSU (North Dakota State University, USA) (2011). Equivalent weights of grains and oilseeds. Available at: http://www.ag.ndsu.edu/pubs/ageng/machine/ae945w.htm. Accessed 23 Jan 2011

PAN Pesticides Database (2009) Available at: http://www.pesticideinfo.org/Search_Chemicals.jsp. Accessed 1 Jan 2009

Pelletier N (2008) Environmental performance in the US broiler poultry sector: life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agric Syst 98:67–73

Piringer G, Steinberg LJ (2006) Reevaluation of energy use in wheat production in the United States. J Ind Ecol 10:149–167

Pollak J (2010) Data update of soybean and soy feedstocks production and life cycle assessment of soy-based products and petroleum-based alternatives, peer reviewed final report. Omni Tech International and Four Elements Consulting. Available at: http://www.biodiesel.org/resources/reportsdatabase/reports/gen/20100201_GEN-422.pdf

Pradhan A, Shrestha S, Mc Aloon A, Yee W, Haas M, Duffield A, Shapouri H (2009) Energy life cycle assessment of soybean biodiesel. U.S. Department of Agriculture, Office of Energy Policy and New Uses. Agricultural economic report no. 845. 10/2002

PRé Consultants (2009) SimaPro 7.1 LCA software. http://www.pre.nl/. Accessed 1 Jan 2009

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. J Dairy Sci 93:1266–1282

Schnitkey G (2004) Estimated cost of crop production in Illinois. Farm business management handbook. Available at: http://www.farmdoc.illinois.edu/manage/enterprise_cost/2004_crop_budgets.pdf

Shapouri H, Duffield JA, Wang M (2002) The energy balance of corn ethanol: an update: U.S. Department of Agriculture, Office of Energy Policy and New Uses. Agricultural economic report no. 813. 7/2002. Available at: http://www.transportation.anl.gov/pdfs/AF/265.pdf

Shapouri H, Duffield JA, Wang M (2003) The energy balance of corn ethanol revisited. U.S. Department of Agriculture, Office of Energy Policy and New Uses. Agricultural economic report number 813

Sheehan J, Camobreco V, Duffield JA, Graboski M, Shapouri H (1998) Life-cycle inventory of biodiesel and petroleum diesel for use in an urban bus. A joint study sponsored by U.S. Department of Agriculture and U.S. Department of Energy. NREL/SR-580-24089 Golden, CO: National Renewable Energy Laboratory. U.S. Department of Energy, 5/1998

Simplified Emission Inventory Tools - SEIT (2006). SEIT calculation workbook; v1.0. US Energy Information Administration, Washington, July 2006

Spatari S, Zhang Y, Maclean HL (2005) Life cycle assessment of switch and corn stover derived ethanol-fueled automobiles. Environ Sci Technol 39:9750–9758

Thoma G, Popp J, Shonnard D, Nutter D, Ulrich R, Matlock M, Kim D, Neiderman Z, East C, Adom F, Kemper N, Maes A (2012) Greenhouse gas emissions from production of fluid milk in the US. Int Dairy J (in press)

USDA NASS (2006) U.S. Department of Agriculture, National Agricultural Statistics Service. Agricultural chemical usage-field crops summary (2005). Available at: http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2006/AgriChemUsFC-05-17-2006.pdf

USDA NASS (2007a) U.S. Department of Agriculture, National Agricultural Statistics Service. Crop production 2006 summary. U.S. Department of Agriculture, 11 Jan 2008. Available at: http://usda.mannlib.cornell.edu/usda/nass/CropProdSu//2000s/2007/CropProdSu-01-12-2007.pdf

USDA NASS (2007b) U.S. Department of Agriculture, National Agricultural Statistics Service. Agricultural chemical usage-field crops summary, 2006. Available at: http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2007/AgriChemUsFC-05-16-2007_revision.pdf

USDA ERS (Economic Research Service) (2009) U.S. fertilizer use and price. Available at: www.ers.usda.gov/Data/FertilizerUse. Accessed 1 Jan 2009

USDA NASS (U.S. Department of Agriculture, National Agricultural Statistics Service) (2009a) Crop production 2008 summary. U.S. Department of Agriculture, 11 January 2008. Available at: http://usda.mannlib.cornell.edu/usda/nass/CropProdSu//2000s/2009/CropProdSu-01-12-2009.pdf

USDA NASS (2009b) U.S. Wheat classes. Available at: http://www.ers.usda.gov/briefing/wheat/background.htm. Accessed 14 Apr 2009

USDA-IL (2010) Illinois Department of Agriculture. Available at: http://www.agr.state.il.us/marketing/index.html. Accessed 23 Feb 2011

USGS (2007) United States Geological Survey 2007 available at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/myb1-2007-stonc.xls http://minerals.usgs.gov/minerals/pubs/commodity/lime/myb1-2007-lime.xls

Van der Werf H, Petit J, Sanders J (2005) The environmental impacts of the production of concentrated feed: the case of pig feed in Bretagne. Agric Syst 83:153–177

Vitosh ML (1996) N-P-K fertilizers, Michigan State University Extension Bulletin. Available at: http://fieldcrop.msu.edu/sites/fieldcrop/files/E0896.pdf

Wang M (2001) Development and use of GREET 1.6 fuel-cycle model for transportation fuels and vehicle technologies. Tech. Rep. ANL/ESD/TM-163, Argonne National Laboratory, Argonne, IL, 2001. Available at: www.transportation.anl.gov/pdfs/TA/153.pdf